

DYNAMICS AND ENERGETICS OF STRONG RADIO SOURCES

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ABSTRACT

The rapid expansion of a cloud of relativistic gas is discussed, and it is shown that the most likely result is a bubble whose magnetic field is primarily confined to the surface and possibly to some threads linking through it. The increase in lifetime, field strength and particle energy density which results is compared to more conventional models. The effect of the intergalactic medium is explicitly included, and the time dependences of the total luminosity, size, and particle energy are calculated for electron number densities obeying both a delta function and a power law in energy.

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I. INTRODUCTION

Because the basic observational data on the strong extragalactic radio sources consists of information concerning their luminosity, polarization, and structure, it is necessary to invoke additional theoretical arguments to discuss their energy content, lifetimes, and evolution. In past discussions of the energetics of such sources it has been customary to assume that the magnetic fields and relativistic electrons responsible for the observed synchrotron radiation are homogeneously distributed throughout the emitting region, and that the energy in the relativistic particles and magnetic fields is determined by minimizing the total energy. In discussing the dynamics and evolution of these sources, the effects of the intergalactic medium usually have been taken to be negligible. However, observations of the detailed radio structure of these sources, particularly of the two emitting regions of Cygnus A (Wade, 1966), indicate that at least the homogeneity assumption, and probably the others also, should be dropped.

In this paper none of the above assumptions are employed; we present instead a general calculation of the dynamics and energetics of strong extragalactic radio sources in which the non-homogeneous magnetic field distribution and the effects of the intergalactic medium are explicitly taken into account. The discussion will be limited to the phase of such sources in which the radiating material is expanding at a high speed in all directions

into the ambient medium. The calculations are largely independent of the assumptions concerning the origin of the magnetic field, so long as it is assumed to be isotropic on a scale comparable with the cloud size. If there is an initially weak external field, the rapid expansion of the cloud at a speed above the external Alfvén speed thus causes this field to be compressed and form a skin in which the pressure of the relativistic particle cloud is essentially balanced by the magnetic field pressure. If one were concerned only with an initially internal field in the cloud, it is very probable that then also a strongly magnetized skin would be formed, since it would always be the magnetic field that would be pushing against the external medium. In this case, however, the pressure of the relativistic gas would assist in providing the required total pressure, and it is only as a result of an uneven distribution of field and particles that is likely to develop that the field would be augmented in the skin.

Initial internal fields will of course be, in general, weakened by the expansion from the cloud, and for the case of a statistically isotropic field, a uniform expansion would result in the magnetic pressure decreasing in step with the decrease in the pressure of the relativistic gas, both according to an adiabatic law with an exponent of $4/3$. In practice it is hard to envision a situation in which the relativistic gas is generated in the region whose magnetic pressure is comparable to that of the gas. As the expansion proceeds, the particle pressure will thus continue to dominate everywhere in the

interior of the bubble, and the only place where the magnetic field pressure and the particle pressure are matched would be at the boundary.

A more detailed discussion would have to be concerned with the instabilities that arise when a high pressure gas is pushing out against the ambient medium at a supersonic or super-Alfvénic speed. It is known that in a case of this kind, the expansion surface is unstable, and the expansion front will tend to become deeply corrugated and leave behind pockets of the external medium. The pressure in the enveloped pockets must of course then rise to the pressure in the interior of the expanding bubble, and a magnetic field so enveloped will thus be augmented by compression. The final result must be a configuration such that the magnetic field pressure is comparable with the relativistic gas pressure everywhere on the boundary of the expanding bubble and in the interior along all the filaments of magnetic field that have become enveloped. As for the interior of the bubble, the magnetic field will have a pressure much below the particle pressure if this was the relation in the early phase of the expansion of the relativistic gas.

Hence the synchrotron emission will be primarily confined to some fraction of the total volume of the source; that is, to the strongly magnetized shell that will be constraining the relativistic gas, or to the compressed filaments of magnetic field that will be threading through it. This type of configuration would fit well with the knowledge we now have concerning the emission from the Cygnus radio source, where it appears that there is a complex structure

within each of the two emitting regions. On a much smaller scale the same type of structure occurs in the Crab Nebula, where there also exists an outer, roughly spherical shell of filaments, as well as numerous internal filaments that seem to be mainly responsible for the synchrotron radiation.

In such a model the synchrotron radiation as a whole will have a different time dependence than in the case of a model where the magnetic field and the relativistic gas are uniformly intermixed. We shall discuss this evolution under the assumption that the external medium is uniform and that the emission is essentially confined to the strong field regions into which the relativistic gas penetrates. In Section 2 we formulate the model and compare the particle energy densities, magnetic field strength, and lifetimes that are obtained for a source of given total luminosity and spectrum with those obtained from the homogeneous, minimum total energy model. In Section 3 we shall calculate and discuss the early stages of the evolution of a radio source fitting this model.

II. FORMULATION

For simplicity, we assume that the relativistic particles in the source are primarily electrons and that their number distribution per unit volume as a function of energy is given by some function $N(E)$. Taking the magnetic field to occupy a fraction f of the total volume of the source, the total luminosity per unit volume due to

synchrotron radiation is

$$L = 2.4 \times 10^{-3} f B^2 \int_{E_L}^{E_H} E^2 N(E) dE \text{ ergs sec}^{-1} \text{ cm}^{-3} \quad (1)$$

where E_L and E_H are the lower and upper energy cutoffs in the electron energy distribution. As discussed in Section 1, the magnetic field in the synchrotron emitting regions is determined by equating the magnetic pressure to the particle pressure. Thus

$$B^2/8\pi = \frac{1}{3} \int_{E_L}^{E_H} E N(E) dE = \frac{1}{3} U \quad (2)$$

where U is the relativistic electron energy density and we have used the ratio of specific heats $\gamma = 4/3$ appropriate to a relativistic gas. Equations (1) and (2) provide a means of calculating the energy content of the relativistic particles and the magnetic field strength in the source if the luminosity and particle energy distribution are known. For a source of given luminosity and energy distribution $N(E)dE \propto E^{-m}dE$ with $2 < m < 3$, as is appropriate to most radio sources, it is interesting to compare our values of the particle energy density and magnetic field strength with those obtained from the homogeneous minimum total energy model. (Since in this model the minimum energy occurs when the magnetic field and particle energy densities are about equal, we shall refer to it as the equipartition model for brevity.) It follows then from equations (1) and (2) that the relativistic electron energy density is larger in the present model by a factor of $(3/f)^{1/2}$ than in the equipartition model, and our magnetic field estimates are larger by a factor of about $(1/3f)^{1/4}$.

We emphasize again that this somewhat larger field is found in only the small fraction f of the source. Defining a characteristic time scale τ for the radio source by

$$\tau = U/L$$

(3)

we see that our characteristic times are longer by a factor of $(3/f)^{1/2}$ than those calculated from the equipartition model. This increase, which arises naturally in our model, should alleviate the time scale problems that have arisen in previous discussions of radio sources. For the present model the values of τ given by equation (3) are likely to be an underestimate, since that expression refers only to the particles that are in the regions of magnetic field and are radiating. However, it is likely that the particles are not trapped in the field and can move about inside the source, thus forming a reservoir of energy in the regions of low magnetic field. The factor by which this effect increases τ of course depends on the geometry of the magnetic field regions. The above results are summarized in Table I.

III. EARLY EVOLUTION OF RADIO SOURCES

The evolution of spectra of radio sources has been discussed by Kardashev (1962) and others, while the dynamics of a spherically expanding source have been considered by van der Laan (1963, 1966) and Shklovskii (1963). In discussing the spectra which change due to both synchrotron and expansion losses, Kardashev considered only

Table I

Equipartition Model		Present Model
Particle Energy density	U	$(3/f)^{\frac{1}{2}}U$
Magnetic field	B	$\sim(1/3f)^{\frac{1}{4}}B$
Lifetime	τ	$>(3/f)^{\frac{1}{2}}\tau$

uniform expansion, and dynamical treatments have to date assumed either a uniform homogeneous magnetic field, or that the expansion is strictly adiabatic, or that the influence of the external medium is negligible. The present discussion of the evolution will make none of the above assumptions. We do not, however, calculate the evolution of the detailed spectrum but rather calculate the evolution of the luminosity. The external medium will be assumed to be uniform and the expansion into it will be assumed to be supersonic or super-Alfvénic.

The energy balance is given by

$$\frac{dp}{dt} = (\gamma-1) \rho \frac{dq}{dt} + \frac{\gamma p}{\rho} \frac{d\rho}{dt} \quad (4)$$

where p is the relativistic electron pressure, ρ the mass density and $\rho \frac{dq}{dt}$ the synchrotron loss per unit volume, with the last term giving the work done by the expansion. For illustrative purposes we first take for the electron energy distribution $N(E)dE = n\delta(E)dE$. While such a distribution is physically unrealistic, the calculations will display all the features of the more realistic inverse power law distributions. Assuming that the initial stages of evolution may be described by a spherical object of radius R evolving from an initial radius R_0 , particle conservation together with equations (1), (2), and (4) yields for the change in electron energy with respect to time

$$\frac{dE}{dt} = -\frac{E}{R} \frac{dR}{dt} - \frac{8\pi}{3} a f n_0 \left(\frac{R_0}{R}\right)^3 E^3 \quad (5)$$

where $a = 2.4 \times 10^{-3}$ in c.g.s. units and n_0 is the initial electron number density. The first term represents the expansion loss and

the second gives the loss due to synchrotron radiation. We shall work with equation (5) rewritten as

$$\frac{dE}{dR} = -\frac{E}{R} - \frac{8\pi}{3} a f n_o \left(\frac{R_o}{R}\right)^3 E^3 \left(\frac{dR}{dt}\right)^{-1}. \quad (6)$$

The equation for dR/dt may be obtained by noting that the work done by the source in moving the external medium ahead of it is

$$pdV = \frac{1}{3} n E 4\pi R^2 dR = \Delta KE = 2\pi R^2 \rho_e \left(\frac{dR}{dt}\right)^2 dR \quad (7)$$

where ρ_e is the density of the external medium. Hence

$$\frac{dR}{dt} = \left[\frac{2}{3} \frac{1}{\rho_e} n_o R_o^3 R^{-3} E \right]^{\frac{1}{2}}. \quad (8)$$

If the accumulation of the external medium on the surface of the expanding bubble can be neglected, ρ_e is a constant. It is doubtful that this is a good approximation, however, since the surface of the cloud will certainly move at velocities which are supersonic relative to the external medium in the early stages of its expansion. The general considerations given in Section 1 preclude any detailed calculation of the dependence upon R of the external density, and we shall in general write

$$\rho_e = \rho_{oe} \left(\frac{R}{R_o}\right)^s \quad (9)$$

This then gives

$$\frac{dR}{dt} = \left[\frac{2}{3} \frac{n_o}{\rho_{oe}} \right]^{\frac{1}{2}} \left(\frac{R_o}{R}\right)^{\frac{s+3}{2}} E^{\frac{1}{2}}. \quad (10)$$

Equations (10) and (6) provide a set of simultaneous differential equations which may be machine integrated to find the electron energy as a function of time or of the source radius. Figure 1 presents the latter in non-dimensional form for the case $s = 0$, $\rho_{oe} = 10^{-30} \text{ gm/cm}^3$, an initial radius of 100 pc., and an initial total energy of 10^{60} ergs. Figure 2 gives the luminosity as a function of radius for the same conditions and two values of s , while Figure 3 shows the luminosity as a function of time for several f and s values. Since it will be seen below that the results of similar calculations for an inverse power law dependence in energy are qualitatively the same as the results presented in Figures 1, 2, and 3 we shall discuss these results now. As is implied by equation (5), the synchrotron losses dominate the expansion losses only at the beginning of the expansion, and the figures show this clearly. The extremely large range of luminosity represented in Figure 3, over fourteen orders of magnitude in an evolution time of 10^6 years, is perhaps a little surprising since it is known that the spread in the observed intrinsic luminosities of the extra-galactic radio sources is only about six decades. However, two points must be borne in mind. In formulating the dR/dt term we have not included the pressure of the intergalactic medium, hence our formulation provides no way of stopping the expansion. The present discussion must thus be considered to refer only to the early stages of evolution. In the latter stages the expansion in all directions must stop (or the sources would not be observable); this expansion may

be halted by intergalactic fields (Gold, 1965) or, if the center of mass of the source is moving relative to the intergalactic medium (e.g., ejection from a parent galaxy), by dynamic effects such as inertial confinement (DeYoung and Axford, 1967). The second point is that the large spread in luminosity shown in Figure 3 is unlikely to be observed since most of the decrease occurs in the first hundred years of evolution. Thus if the expansion ceases at about 10^6 years, with the subsequent decrease in luminosity due only to synchrotron losses, in a random sample of radio sources one would expect at most 1/1000 of the sources in the sample to have luminosities outside a range of about six orders of magnitude.

The calculations with $f = 1.0$ correspond to the magnetic field completely filling the radio source volume and provide the closest comparison with the equipartition model. It is seen, as expected, that the models with $f < 1$ evolve more slowly, as do those with $s > 1$.

We now assume the number of electrons per unit volume in the energy range between E and $E + dE$ to be given by $N(E)dE = kE^{-m}dE$. The conservation of particle number implies, for spherical geometry,

$$kE^{1-m} \Big|_L^H = (1-m)n_0 \left(\frac{R_0}{R} \right)^3 \quad (11)$$

while energy per unit volume is

$$U = \int_L^H E n(E) dE = n_0 \frac{(1-m) E^{2-m} \Big|_L^H}{(2-m) E^{1-m} \Big|_L^H} \quad (12)$$

Differentiation of equation (12) with respect to time and substitution into equation (6) will produce terms involving dE_H/dt and dE_L/dt , where again E_L and E_H are the lower and upper limits of the electron energy. Some simplification may be achieved by specifying the range of the exponent m and the relative size of the energy limits. Data from a large number of radio sources (Maltby, Matthews, and Moffet, 1965) indicates that a good average for m is $m \sim 2.5$, and the range of electron energies which corresponds to the frequency range over which a power law is roughly obeyed covers several orders of magnitude. Hence $E_H \gg E_L$, and for $2 < m < 3$, the low energy term only may be retained in expressions of the form $(E_H^{\alpha-m} \pm E_L^{\alpha-m})$ as long as α is less than m . As the synchrotron loss per particle is proportional to $E^2 B^2$ however, $dE_H/dt \gg dE_L/dt$, and terms involving the product $E^{-m}(dE/dt)$ must be retained for both high and low energies. Because of our choice of m , only the lower limit will be used in Equation (12), which in turn determines the value of the magnetic field. Physically this implies that the energy spectrum is so steep that most of the energy per unit volume is due to the lower energy electrons, their much greater numbers more than compensating for their deficiency in energy. Since the high energy electrons experience synchrotron effects markedly more than those less well endowed with energy, we shall be interested in the behavior of E_H with time (for $m < 3$ E_H alone can be used in the luminosity equation), and hereinafter we set $E_H = E$. The above arguments imply

that the low energy electrons are degraded primarily by expansion cooling, and we shall put

$$E_L = E_{oL} \frac{R_o}{R} \quad (13)$$

Substitution of all of the above into Equation (6) gives

$$\frac{dE}{dt} \left(E^{1-m} + \frac{(1-m)}{(2-m)} E_L E^{-m} \right) = \left(1 + \frac{1-m}{2-m} \right) E_L^{1-m} \frac{dE_L}{dt} + \frac{3}{2-m} E_L^{2-m} \frac{1}{R} \frac{dR}{dt} (1+\gamma) - \frac{8\pi a f k E_L^{2-m} E^{3-m}}{3(3-m)(m-2)} \quad (14)$$

The second term in parentheses on the left hand side of the above equation is much less than the first and decreases with increasing R. Hence it will be dropped. The derivation of dR/dt proceeds exactly as before, except that Equation (12) must be used, which gives

$$\frac{dR}{dt} = \left[\frac{2}{3} \frac{n_o}{\rho_{oe}} \frac{m-1}{m-2} E_{oL} \right]^{\frac{1}{2}} \left(\frac{R_o}{R} \right)^{\frac{4+s}{2}} = A \left(\frac{R_o}{R} \right)^{\frac{4+s}{2}} \quad (15)$$

These equations may again be numerically integrated to find E as a function of time, which is substituted into

$$L_T = 2.4 \times 10^{-3} B^2 \text{ kfV} \frac{E^{3-m}}{3-m} \text{ erg sec}^{-1} \quad (16)$$

to find the luminosity as a function of time. These results have been calculated for the same initial values as used for the delta function distribution. Figure 4 gives the upper electron energy as a function of the radius of the object, while Figures 5 and 6 show the luminosity as a function of radius and time respectively.

The changes in energy and luminosity for various values of f and s are, as mentioned above, similar to the results for the delta function distribution, though not as pronounced. However, the discussion presented there applies equally well to the power law calculation. Thus for both distributions, the present model provides the advantages of a longer lifetime and less stringent requirements upon the magnetic field than does the equipartition model.

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FIGURES

- Figure 1. Relative electron energy as a function of cloud radius.
 $N(E) = \delta(E)$.
- Figure 2. Total luminosity as a function of cloud radius.
 $N(E) = \delta(E)$.
- Figure 3. Total synchrotron luminosity as a function of epoch.
 $N(E) = \delta(E)$.
- Figure 4. High electron energy as a function of cloud radius
for power law spectrum.
- Figure 5. Total synchrotron luminosity as a function of cloud
radius for power law spectrum.
- Figure 6. Total synchrotron luminosity as a function of epoch
for power law spectrum.











